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Influencing factors of water electrolysis electrical efficiency

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ABSTRACT

As a promising method of hydrogen production by utilizing renewable energy sources for future, water electrolysis is one of the favorite fields of the study and scientific experiment for many researchers all around the world. One of the most popular related research areas is the efficiency enhancement of the process by the means of reducing the electric power consumption in electrolysers. Regarding to different effective factors related to this issue, many efforts have been done to reach elevated levels of current densities by maintaining or even reducing the electrolysis cell voltage. According to this matter, recommendations could be given for reaching higher process efficiencies. This paper analyzes the factors with an influence on water electrolysis efficiency by studying available verified information in the electrical, electrochemical, chemical, thermodynamics and fluid mechanics fields.

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Contents

1. Introduction

Hydrogen production by the means of water electrolysis has been studied for a long time [1,2]. Some available records show that hydrogen has been used by man as an alternative substance in many different fields such as commercial, military and industrial sectors since the late 19th century [3]. Nowadays, only 4–5% [4,5] of total global production of this most abundant substance of the universe [6,7] is being done by water electrolysis. As the water molecule has a very much stable structure in ambient temperature, the required energy to decompose it via electrolysis is relatively high [8]. The most deficiency of the commercial and industrial grade electrolysis systems is their expensive gas production costs. Electricity power demand expense constitutes the largest fraction [9] of hydrogen production costs by using electrolysis method. In industrial electrolysis devices, a large current density is used to break the water molecules into hydrogen and oxygen. The overall equation of this reaction is noted as below:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (1)$$

The required voltage for splitting a molecule of water is approximately 1.23 V in laboratory conditions which is also called the equilibrium voltage. However, in practical electrolysis cells, higher voltage is required. This matter is caused by overpotential level

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of the electrochemical reaction [10]. The value of overpotential is affected by many different factors, which are going to be discussed in the next sections of this paper. By following the Ohm's law Eq. (2) and the electric power Eq. (3):

$$U = RI \tag{2}$$

$$P = UI \tag{3}$$

where U is the electrical potential in volts, I is the electric current in Amperes, R is the electrical resistance in Ohms and P is the electric power in Watts. It is obvious that in massive current level electrolysers, any slight increase in the cell voltage could increase extra hundreds or even thousands of Watts in system power demand and consumption because the deal is with low voltage and high current levels.

Massive current densities cause a remarkable ohmic potential drop between the electrodes and as a result, higher electrical power loss and less process efficiency are inevitable. Many efforts have been done in order to reduce the required applied voltage. The main causes of the above-mentioned overvoltage and suggested methods to reduce their effect are introduced and discussed as below.

2. Factors with an influence on electrical efficiency

2.1. Electrolyte quality

As it is known, the bases and acids which are used to change the nonconductive nature of pure water have a great effect on the required voltage to drive an electrolytic bath on a certain current density [11,12]. This fact is a result of the ionic conductivity quality of an electrolyte. On the other hand, corrosive nature of these materials, limit the use of very high concentrated acidic and alkali electrolytes in industrial electrolysers where it has negative effects on the life time of electrodes and some other compartments of the system. Considering the mentioned matters, 25–30% KOH solution in water has been widely used in electrolysers for a long time [13].

It is known that the electrocatalytic performance of today's common electrolysis cells is limited [14,15]. This limitation causes efficiency reduction as the overall electrical resistance of the system is affected by the mentioned parameter. Therefore, replacements such as ionic liquids are recently introduced to improve the conductivity and stability factors of electrolytic solutions [16,17]. de Souza et al. [18] performed a research on using an ionic liquid sample of 1-butyl-3-methyl-imidazolium-tetrafluoroborate (BMI.BF4) [19] in water as an electrolyte solution (which is treated as an inexpensive material) in ambient temperature using some easily found electrode materials such as carbon steel (CS), nickel (Ni), nickel–molybdenum (Ni–Mo) alloy and molybdenum (Mo). An efficiency rate of 96% was recorded by some researchers in the case of using low carbon steel electrodes [20] in 10 vol.% of MBI.MF4. This experiment has been done under a current density value of 44 mA cm^{-2}. The recorded efficiency is larger than those of today's commercial and industrial grade electrolysers which are usually less than 73% [21]. However, it should be considered that most of such electrolysers run under much higher current densities than this experimental value.

In addition to the above-mentioned, existence of impurities has some other effects in order to reduce the efficiency and conducting side reactions [22] as well. Magnesium or some other ionic contaminations such as chloride or calcium ions could be expressed as examples of these materials. Moreover, contaminations could block and passivate the electrodes and/or the membrane surfaces [11,23] which sabotages the mass and electron transfer. The latter indeed, is another cause of the ohmic resistance increase in the electric current path.

2.2. Temperature

Temperature is known as one of the most effective variables on the electric power demand of an electrolysis apparatus. Electrolysis is more efficient in higher temperatures [20]. This behavior could be discussed according to the thermodynamic characteristics of a water molecule, where its splitting reaction potential is known to reduce as the temperature increases. In addition, surface reaction and ionic conductivity of an electrolyte are expected to be raised with temperature [24]. Performing the electrolysis process in higher temperatures showed a lower amount of the applied voltage requirement in order to reach same levels of current density [25,26]. This fact has been known and studied for a few decades. Bailleux [27] monitored the operation of a test hydrogen production plant for two years. As it would be predictable, technology of the plant was much simpler back in early 1980s in contrast with today. The report shows that the plant ran on 40 wt% potassium hydroxide alkaline solution, pressure level of 20 bar, current density of 10 kA m^{-2} and temperature range of 120–160 °C. Proper data scanners were used to monitor the current density, voltage, temperature, pressure and gas purity. The latter was required in order to calculate unwanted gas contents of each oxygen and hydrogen outlet. The research reported a 120 mV reduction in the required voltage as the temperature raised from 120 °C to 150 °C. In contrast with this achievement, this report clearly mentions some sorts of "stability problems" such as cracks and gasket leaks, which were caused by system temperature and pressure.

In most of the recent researches, high temperature electrolysis aim much higher temperature ranges. As an example of such sort of experiments, the research results of Fu et al. [28] who have analyzed the thermodynamic aspects of a high temperature steam electrolyser could be mentioned. This experiment was conducted to analyze electrochemical behavior and thermodynamic characteristics of a high temperature steam electrolyser (HTSE) in order to study its efficiency. The research outcome stated clearly that water electrolysis in high temperatures requires less energy than the conventional low temperature electrolysis process. Moreover, efficiency of high temperature electrolysis is at higher levels in analogy with those of low temperature processes. Authors of the above-mentioned paper divided the efficiency of an electrolysis process into three individual parameters: electrical efficiency, electrolysis efficiency and thermal efficiency. They calculated the share of each one of them in overall efficiency were 70%, 22% and 8%, respectively. An increase in the temperature of the process showed a raise level in the share of thermal efficiency in the overall as the electrical efficiency decreased gradually. In this case, electrolysis efficiency almost did not change. The report also covered the results of coupling the HTSE with a high temperature gas cooled reactor (HTGR). When the electrolysis temperature was increased up to 1000 °C, the overall process efficiency changed from 33% to 59%, which is claimed to be over two times more than the efficiency of a conventional alkaline water electrolyser in the same time and made by similar technology.

Moreover, Ganley [29] studied the electrolysis process efficiency of a high temperature and pressure electrolyte (steam). A chemical resistant cell was used to carry out this experiment as the sample electrolyte was a high concentration KOH solution heated up to 400 °C and compressed to different extents. The electrolyte concentration sat to be 19 M at the starting phase of each test, which is, highly corrosive to many metals and alloys. The other variable was the electrodes material which will be discussed in Section 2.5. Results of conducting the experiments at the atmospheric pressure and different temperature levels between 200 °C and 400 °C showed an acceptable fall in the amount of required applied voltage in the case of targeting any given current density. Outcome graphs showed that in the experimental electrolysis apparatus

of the research, more than 1.8 V is required to be applied to the electrodes for reaching a current density of 200 mA cm^{-2} as the electrolyte is heated up to 200 °C. The amount of required voltage in same conditions of pressure and current density is about 1.5 V while the electrolyte is heated up to 400 °C.

Nagai et al. [30] expressed that conducting electrolysis in higher temperatures decrease the "reversible" potential of water (also known as the equilibrium voltage). On the other hand, it also enlarges the gas bubbles size and reduces their rising velocity. Both of the latter mentioned, lead to larger void fraction in the electrolyte and decrease the efficiency as a result. Void fraction will be discussed in detail in Section 2.3.

In addition, Ulleberg [14] conducted a research to build a model of the electrolysis process. The obtained thermodynamic and electrochemical model, showed clearly a remarkable reduction in both reversible potential and over voltage of the system in high temperatures. This conclusion is also supported by comparing the drawn current versus voltage curves in both cases of low and high temperature electrolysis. Remarkably more efficient process efficiencies could be mentioned as the resultant of all mentioned effects of conducting the electrolysis in higher temperatures.

Conducting water electrolysis in very high temperatures on gas state electrolyte seems to have a higher efficiency than the low temperature systems, although, physical, mechanical and life time stability of the electrolysis cells might still remain a concern for the designers and manufacturers of commercial and industrial electrolysers.

2.3. Pressure

Pressure level is another factor with an influence on electrolysis efficiency. Mansouri et al. [31] tried to increase the efficiency and lower the capital costs of hydrogen production by reaching higher current densities in the conventional electrolysers. Research results showed that increasing electrolyte pressure leads to less power consumption as it reduces the diameter of produced gas bubbles. Therefore, the ohmic voltage drop and power dissipation between electrodes are reduced. In addition, high pressure water electrolysis reduces the amount of required power for further compression of the product which is an energy consuming process. This experiment was conducted in a conventional three compartment electrolysis cell where the temperature was a controllable variable between 25 °C and 90 °C. Electrical current density was maintained at 1 mA cm^{-2} and the sample electrolyte was either a 34 wt% or 25 wt% KOH solution in distilled water. The electrodes were made up of smooth nickel (Ni 200) and pure platinum (99.99%) plates with a 1 cm^2 surface area. Authors measured an overall voltage reduction of up to 100 mV when the electrolysis process was taking place under the pressure of 30 atm. On the other hand, no further significant voltage reduction was recorded for higher pressure values (up to 40 atm) in the case of high current densities. The cell voltage–pressure graph had its highest reduction slope when the pressure was raised from 1 atm to 10 atm for all temperature values.

Onda et al. [32] also expressed that compressing water consumes much less energy comparing to the energy required for compressing gas state hydrogen. The authors' calculations were based on a research done by LeRoy et al. [33] and estimated the ideal pressure and temperature conditions of hydrogen production by the means of water electrolysis to be relatively up to 70 MPa and 250 °C. Considering enthalpy and Gibbs energy changes, water electrolysis voltage is mentioned to decrease as the temperature rises in high pressures and vice versa. However, in the case of pressure levels higher than 20 MPa, they found the voltage rise to be small when the temperature falls. At last they mentioned the possibility of a 5% efficiency enhancement in the electrolysis phase and 50% in the compression phase of hydrogen production using high pressure water electrolysis.

2.4. Electrical resistance of the electrolyte

Electrical resistance of an object is an evaluation of its opposition to the passage of electric current. The value of this opposition is proportional to the object's length, cross section area of the current path and the material resistivity. The relationship between the mentioned factors is shown in Eq. (4) as bellow.

$$R = \frac{\rho l}{A} \tag{4}$$

where R is the electrical resistance, ρ is the material resistivity, A is the cross section area and l is the length of the current path. Electrons start their travel from the surface of an electrode, move through the electrolyte and finally end their journey to the surface of the other electrode. This path could be assumed as an object with the same length as the distance between electrodes, the cross section of the area of electrodes and the resistivity which is a compound of different factors such as the electrode material, electrical admittance of the electrolyte and the surface reaction between electrodes and electrolyte. By at the whole compound as a single object, there are some factors, which are able to change its resistance. These factors are discussed as below:

2.4.1. Space between the electrodes

Eq. (4) clearly expresses that by reducing the space between electrodes, lower electrical resistance could be obtained. However, the question may occur that how much distance reduction is possible? Nagai et al. [30] carried out a series of experiments to find the optimum space between electrodes regarding to this subject. Their research was based on examining the effects of void fracture between the electrodes which is caused by the existence of the produced gas bubbles.

The electrolysis cell of the above-mentioned research was subjected to the atmospheric pressure with Ni–Cr–Fe alloy made electrodes. Other variables of this research were the current density, system temperature and electrodes distance, size, wettability and inclination as the test electrolyte was 10 wt% potassium hydroxide aqueous solution. The results of this research clearly show that too much reduction of the space between electrodes will increase the void fracture and finally cause a less efficient process. This effect was much more sensible in the case of higher current densities. By comparing the applied cell voltage and passing current levels while electrodes were placed in different distances, the authors stated that positioning the electrodes too close to each other will cause a reduction in the process efficiency. This phenomenon was also studied earlier by LeRoy et al. [34] and it was pointed out that the increase of gas volume between electrodes will lead to higher electrical resistance and efficiency decrease of water electrolysis.

2.4.2. Size and alignment of the electrodes

Another variable of Eq. (4) is the object cross section area. According to this equation, using electrodes with larger surface area could result in lower electrical resistance. Again in this case, it would be much better to define the term "more surface area" in practice. The question is whether the only limit for using larger electrodes is the manufacturing, mechanical, dimensional and technical limits of the apparatus? Referring to the previous mentioned paper [30], the authors conducted a series of experiments in order to compare the results of using different electrode sizes in order to calculate their effect on electrolysis efficiency. The results were really noteworthy as they found out in the case of using the same electrode width, an increase in its height, leads to a requirement

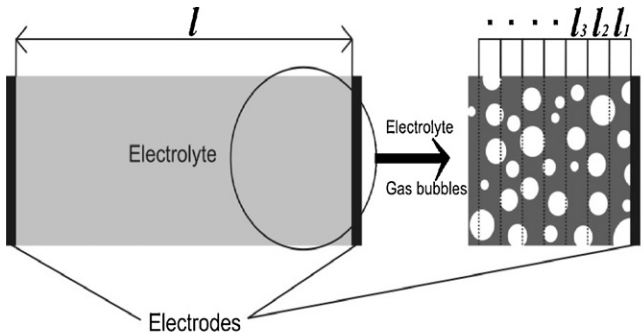


Fig. 1. Void fraction formation in an electrolyte.

of more applied cell voltage. The reason was stated to be the formation of a larger void fraction caused by gas bubbles in higher altitudes. The model of gas bubbles movement [35] clearly shows bubble accumulation in higher parts of the electrodes.

The latter experiments [30] also showed that placing the electrodes in vertical mode is the best choice in order to obtain minimal ohmic resistance regarding to the bubble departure behavior.

2.4.3. Forcing the bubbles to leave

Ohmic resistance in an electrolysis bath is proportional to the bubble coverage of all surfaces as it causes less conductivity and more ohmic drop [36]. Bubble diameter is related to current density and pressure, as higher current density and lower pressure cause a formation of larger diameter gas bubbles [37]. Gas bubbles disengagement rate and their departure velocity from electrodes, separator plate and electrolyte surface and space between electrodes play a remarkable rule in the electrical resistance value of an electrolysis cell. Fig. 1 can justify this subject. In this figure, the distance between electrodes "l" is broken to n smaller segments "l_i". Therefore, Eq. (4) could be used to calculate the resistance for each partial length of l_i and as the efficient cross section area for each l_i is significantly reduced by the presence of gas bubbles, the total amount of R increases.

Hence, Eq. (4) could be re-written as bellow:

$$R = \frac{\rho}{A}\left(\sum l_i\right) \tag{5}$$

Eq. (5) and Fig. 1 show the effect of void fracture caused by gas bubbles, which was the subject of debate in Sections 2.4.1 and 2.4.2. Efforts have been done to force the bubbles to detach from surfaces and leave the environment as fast as possible. For instance, Li et al. [38] exposed their experimental electrolysis apparatus to an ultrasonic field. System efficiency and energy consumption were recorded in both cases of presence and absence of the ultrasonic field. The presence of an ultrasonic field caused a large reduction in cell voltage, especially in high current densities and low electrolyte concentrations. The improvement was reported to be 15–18% in high current density experiments, which caused an energy saving of 10–25% in a certain electrolyte concentration. Disengagement of bubbles from electrodes, membrane and the electrolyte is of a great importance in order to improve both local mass and heat transfer in addition to efficiency enhancement. The energy requirement for the ultrasonic field generation could be ignored in analogy with the electrolysis power demand. A 0.05 kW ultrasonic generator was mentioned to be enough for being used on a 100 kA electrolysis cell. In this case, applying the ultrasonic field caused a 30 kW reduction in system energy consumption.

Another set of experiments were done by Wang et al. [39] to lower those cell losses caused by adsorbed gas bubbles on the electrodes and membrane. Exposing the cell to a super gravity field was the concept of this research. Super gravity conditions could be reached by different means, including centrifugal (rotating) installation of a horizontal electrolytic cell. In this experiment, the input and output signals were read by making proper arrangements on the apparatus top and bottom axis. Cell temperature was maintained to 333 K using a water bath. It was known prior to this research that high gravity acceleration environment increases both velocities of convection flow and inter-phase slip [40]. This effect leads to better multiphase separation in gas–liquid and gas–solid phases [41] which, in other words, means improved gas bubble disengagement and departure in an electrolysis apparatus. Hence, referring to the previous sections of this paper, lower ohmic loss and over potential occurs. Wang et al. [39] measured and compared the required voltage for reaching different current densities in different gravity conditions. The results showed remarkable reduction levels of required voltage in the cases of higher gravity values than lower values. This difference became more significant as the current density increased. Authors mentioned significant enhancement in electrolysis efficiency by subjecting the cell to a super gravity field. Regarding to the system power demand, this method is stated by the authors to be efficient enough to be used in industry. For instance, in a 100 kA industrial electrolytic cell with a current density of 0.5 A cm^{-2}, it takes 3 kW of electrical power to reach a gravity value of 161 where it causes a reduction of 0.51 V in required applied voltage which means a 51 kW lowering in power demand and consumption.

2.5. Electrode material

There are a variety of materials used as electrodes in electrolysers. Each metal has a different level of activity, electrical resistance, resistivity against corrosion and life time. Platinum and gold are known to be two of the best choices for being used as electrodes, though they are not popular materials to be utilized for industrial and commercial uses due to their high price. Nickel, Raney nickel and cobalt are common electrode materials for being used in alkaline solution electrolytic baths because their price, corrosion resistance and chemical stability are at satisfactory levels [21].

A number of researches have studied the effect of using different material made electrodes on the electrolysis process. Mansouri et al. [31] repeated their experiments with a number of different electrodes such as Ni, Pt, Ir and Rh all at high purity levels of (99.99%). In addition, the following materials were tested as well: Ni cloth, Ni sinter, Ni–Cd and low impregnation Nickel and cobalt molybdate catalyst on nickel sinter. In order to obtain stable potentials, all the electrodes were pre-anodized. Regarding to the obtained results, nickel showed better potential characteristics than other tested metals. Comparing the recorded system results, authors found out that a woven or porous sintered electrode activity is 30 times higher than smooth electrodes. The reason is expressed to be larger electrode surface area in these cases. Authors mentioned the "apparent exchange current density" as the major cause of this difference, which absolutely makes sense considering higher contact area, electrode bubble coverage and current density.

Any electrolyte has its own performance in contact with different electrodes. For example, platinum electrodes show much higher levels of activity while being used with KOH electrolyte solutions compared to molybdenum. In the case of using BMI.BF4 ionic liquid electrolyte in ambient temperature, electrolysis has a much better performance with molybdenum electrodes [18].

2.6. Separator material

Placing a separator between electrodes reduces the electrolysis efficiency as it blocks the free movement of mass and ions. Moreover, presence of a separator causes more accumulation of gas bubbles in the electrolyte [30] and increases the void

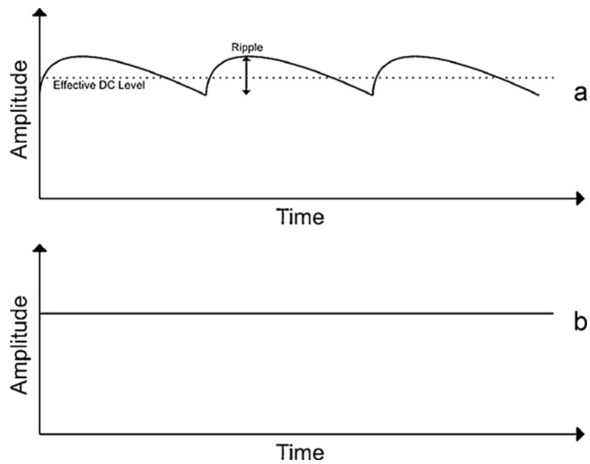


Fig. 2. (a) Steady DC voltage waveform. (b) Smooth DC voltage waveform.

fracture. In addition, the effective electrical resistance of a separator is frequently as large as three to five times of the electrolyte [42].

Electrical resistance of a separator depends on different variables of the system such as corrosion, temperature and pressure [43]. By measuring and comparing the electrical resistance of an electrolyte with a known conductivity or determined solution molarity in the presence of separators made up of different materials, it is possible to classify and pick out and use the best case. There are many different materials and technologies introduced for building separator plates until the date. Back to middle 90s some researchers named asbestos as the best choice for diaphragms because of its wettable and highly porous structure, which showed a low electrical resistance in action [44]. Asbestos, however, is known to be toxic and hazardous [44–47]. Nowadays there are different solutions, materials and technologies available to reduce the negative electrical effect of separators [45,46,48–50].

2.7. Applied voltage waveform

It is almost common for electrolysis systems to use a steady (Fig. 2a) or smooth (Fig. 2b) DC voltage to polarize and decompose the electrolyte.

Referring to the Ohm's law, applied DC voltage U causes the current I to pass through the electrolyte with the resistance of R. This law is stated by Eq. (2). By applying a determined voltage level to an electrolyte, certain current density could be achieved. There are different methods to apply voltage to the electrolytic bath. Shimizu et al. [51] conducted an experiment and checked its behavior while the applied voltage was selected to be in the form of ultra short pulses. The goal of their research was to generate hydrogen with higher applied power without causing a reduction in the process efficiency. They used an electrolysis bath filled with 1 M KOH aqueous solution. The electrodes were made up of platinum plates and they were placed in a 3 cm distance from each other inside the bath. Solution temperature was maintained to 293 ± 2 K for the experiment. The results were recorded and compared in both cases of using a conventional DC power supply and an ultra short pulse power supply with an output pulse width of about 300 ns. Output frequency and peak voltage of this power supply varied from 2 kHz to 25 kHz and 7.9 V to 140 V, respectively.

When an ultra short pulse is applied to an electrolytic bath, there is not enough time for a stable double layer or diffusion layer to form. These times were calculated by the authors to be 3 μs for the mentioned sample electrolyte. The pulse width was needed to be much shorter than this value. Therefore, a coefficient of 0.1 was

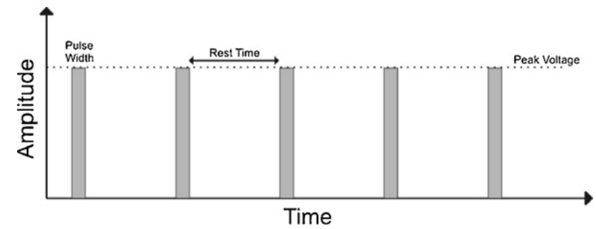


Fig. 3. Ultra short pulse waveform.

chosen. A pulse width of 3 ns is also much less than the required time for the formation of a stable double layer which is known to be in the order of several hundreds of milliseconds. A sample waveform of applied ultra short pulse is illustrated in Fig. 3.

In the case of using a DC power supply, the production rate versus input power graph deviated more from the ideal graph as the input power was increased. Moreover, the efficiency reduction was significant (the recorded efficiency in the case of 0.25 W was up to 5 times more than the case of 250 W).

Results of conducting electrolysis by using an ultra short pulse power supply show that rising input power of the system (by raising the power supply output frequency) does not decrease the efficiency where the efficiency increases by lowering the peak voltage. The probable reason of this issue is expressed to be a lower electron energy level and sharper pulse waveform in reduced voltage peaks.

According to the result of the mentioned research, the question may occur that whether there is a relation between peak voltage and frequency in order to reach the highest possible efficiency. Furthermore, it might be helpful to examine other values of pulse width in order to test its effects on the process behavior.

In another related research to this subject, Ursúa et al. [52] firstly characterized a commercial electrolyser unit. The apparatus could work under the conditions of: 0–120 A electric current and thermal range from room temperature to 65 °C (nominal temperature of the unit). Two power supplies with different topologies were attached to the system in order to test system behavior, efficiency and power and energy consumption.

The first power supply was thyristor based, which regulates its output waveform by controlling the switching time of an electronic switch placed in series with its AC power input line. This power supply topology works at the input power frequency which is either 50 Hz or 60 Hz, depending on local frequency of the power grid. Studying the results of attaching this kind of power supply to the electrolysis cell, shows a non-continues voltage and current waveform and a wide distribution of input current harmonics over different frequencies. The highest achieved efficiency by using this kind of power supply was 70.9%.

The other tested power supply topology was a transistor-based type. This topology works at a much higher frequency range than the previous one. In this case, a main switching system controls the output voltage. A transistor (could be of any kind) works as the heart of this switching system. In the case of using this power supply, the cell voltage and current had an almost pure DC wave form and the harmonics were negligible. A highest efficiency of 77.6% was observed while using this power supply topology.

Comparing the results of both mentioned cases, using a transistor based power supply caused up to 10% more efficient conversion than a thyristor based one.

Unfortunately there are few reports available on studying the electrolysis from the electrical point of view. It is common to use the electrical characteristics of the system such as (voltage, current and current density) to test the theories or as an evidence for comparing different electrochemical methods. However, the applied electrical power is an important part of the electrolysis process and more researches could be conducted on this subject.

Brad [53] and Armstrong and Henderson [54] introduced very similar equivalent electrical circuits for an electrolysis cell. These circuits consider the electrical resistance of the electrolysis system to be in the form of non-linear impedances, including capacitors and faradic elements. In almost every research conducted on the electrolysis of water the output of a DC power source had been fed to the experimental setup and results were studied regarding to the plain ohmic electrical behavior of the electrolyte. Referring the mentioned equivalent electrical circuits, more researches are required to find the best method of applying electrical power in order to conduct efficient water electrolysis.

3. Conclusion

Analyzing the efficiency of the water electrolysis process is a very sophisticated subject. Chemical formulation of the electrolyte has a great effect on the electrical resistance of electrolysis cell. In addition, unwanted side reactions could be prevented by reducing electrolyte contaminations.

Another factor with an influence on electrolysis efficiency is the process temperature. The experimental results show lower splitting reaction potential and reduced electrolyte electrical resistance, increased electrode surface activity and higher efficiency are achieved in increased electrolysis cell temperatures. In addition, conducting electrolysis in raised pressure levels leads to more efficient processes as the void fracture between electrodes is reduced due to smaller size of generated gas bubbles. This reduction in bubbles sizes also affect the effective contact area between electrodes and electrolyte, which results in lower ohmic resistance and required cell voltage.

In order to minimize the effect of gas bubbles and increase the efficiency, some methods are being used such as subjecting the cell to an ultrasonic field or a super gravity condition. On the other hand, physical setup of the electrolysis cell is an important factor which affects the process behavior and cell characteristics.

Distance between electrodes, their size, alignment and shape could be classified in this category. Parallel electrodes with larger surface area, dissipate less power. On the other hand, there is an optimum value for electrodes distance and height. New technologies and materials have also been utilized to enhancing electrodes electrochemical activity and separator plate mass and ion transfer resistance.

Moreover, in an electrochemical process, electrical behavior and characteristics of the process, remarkably affect the efficiency. Electrolysis efficiency has been studied in the cases applying different voltage waveforms. Results of such experiments show how electrolysis efficiency is depended on voltage value in DC power application and its frequency, pulse width and amplitude in pulsar and AC application of electrical current. In each case, there is an optimum combination of the mentioned variables in order to reach the highest possible efficiency.

Regarding to the importance of efficiency enhancement of water electrolysis, this subject could be a field of interest for researchers and scientists from many areas of science and engineering.

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